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Supplementary material

Appendix 1 – Detailed methods for case study

Study area

We apply our statistical framework for comparing biodiversity models to a conservation case study in the fragmented, peri-urban landscape surrounding Montreal, Canada (centered on 45°400N, 73°150W). The landscape covers approximately 27 500 km^2, the majority of which occurs in the fertile lowlands of the St. Lawrence River valley where small forest fragments are surrounded by agricultural and urban areas. This central agro-forested ecosystem lies between two large, contiguous forested areas to the south-east and north-west that are part of the Appalachian and Laurentian Mountains, respectively (Fig. 1; Rayfield et al. 2016).

Land-use change has extensively altered the forest (Brisson and Bouchard 2003, Sokpoh 2010), resulting in 25% forest cover remaining within the St. Lawrence Lowlands as of 2000 (Ministère des ressources naturelles du Québec 2000). Conserving forest biodiversity within this landscape requires a good understanding of the distribution of species across current forest fragments as well as the distribution of species across future forest fragments that are the result of ongoing land-use changes. We compare the three model classes (patch area, patch isolation, environmental conditions) in terms of their ability to characterize present and predict future distributions of 8 vertebrate focal species that characterize the forest biodiversity of this region (Table 2).

Landscape data

We define a forest patch as clusters of habitat pixels that are big enough and close enough together to be used by a particular species. For delineating 'patches' of forested habitat we balanced the trade-off between the number of patches (dataset easily handled below ~ 10 000 patches) and a grain size appropriate for the range of our target species' perceptions (Kotliar and Wiens 1990, Li and Gar-On Yeh 2004, Baguette and Van Dyck 2007). Within the St-Lawrence lowlands, forest patches that were within 30 m of each other were thus grouped into single patches, which assumes a minimal dispersal probability of 0.3. We kept only patches larger than the minimum areal requirements for our 8 focal species (i.e. > 0.2 ha, Table 2). In this landscape, the forest patches within each of the two mountain areas are highly contiguous and therefore, we assume they function as sources for species in the lowlands. We did not predict the probability of occurrence of each focal species in these patches. In the end, our current landscape was composed of 7,235 patches with a median patch area of 42,300 m^2 belonging to the lowlands on which the SAR, MEP, and SDM models were calibrated (Fig. 1, 2).

We extracted a series of environmental conditions for each patch: average soil drainage per patch (high drainage = 1 to poor = 6; IRDA 2005), percentage of forest area covered with deciduous, and coniferous stands, and maximum stand age (Ministère des ressources naturelles du Québec 2000), dominant rock deposit type (4 main types: glacial, fluvial, marine or others; Ministère des ressources naturelles du Québec 2004) and presence of wetlands (GeoMont and Canard Illimités Canada 2008; ν_{mx} in the statistical framework).

Species data

We selected three amphibian and five bird species to represent the diversity of species occurring within our study area and their range of habitat requirements, population dynamics and dispersal abilities with a set of operational entities (Opdam et al. 2008, Table 2). These species differ in key traits including habitat preferences, dispersal abilities, and life history traits, which will allow us maximum contrast for evaluating species response to land-use change.

Amphibians

We extracted occurrence records for three amphibian species; American toad (*Bufo americanus*), wood frog (*Rana sylvatica*), and redback salamander (*Plethodon cinereus*) between 1990-2011 from the Atlas of amphibians and reptiles of Quebec (Société d'histoire naturelle de la vallée du Saint-Laurent 2008). We assumed that American toads and wood frogs could be found within 600m from a breeding pond (Baldwin et al. 2006, Semtlich 2008) and therefore we created a 600m radius buffer around each occurrence point for these species. Similarly, we assumed that redback salamanders will not travel more than 60m outside a forested region (Marsh et al. 2004) and therefore we created a 60m radius buffer around each occurrence point for this species. Forest patches that intersected these buffered points were considered patches where these species occurred. Our final data set included 577, 456, and 52 patches with the occurrence of *B. americanus*, *R. sylvatica*, and *P. cinereus*, respectively.

Birds

We extracted occurrence records for five bird species; pileated woodpecker (*Dryocopus pileatus*), American woodpecker (*Scolopax minor*), ovenbird (*Seiurus aurocapilla*), red-breasted nuthatch (*Sitta canadensis*), and barred owl (*Strix varia*) between 1990 and 2015 from ebird (ebird 2012). We created 60m radius buffers around occurrence points for forest interior bird species (ovenbird and red-breasted nuthatch; Desrochers and Hannon 1997, Bayne and Hobson 2001, Belisle and Desrochers 2002) and 200m radius buffers around occurrence points for the remaining bird species (Wishart and Bider 1976, Haney 1997). Forest patches that intersected these buffered points were considered patches where these species occurred. Our final data set included 431, 55, 69, 144, and 120 patches with the occurrence of *D. pileatus*, *S. minor*, *S. aurocapilla*, *S. canadensis*, and *S. varia*, respectively.

Model hypotheses

We used species' dispersal and habitat preference traits (Table 2) to hypothesize which model would best fit species distributions. We expected environmental condition models to best fit species that were specialized on specific forest types and those sensitive to landscape elements beyond just forest composition (*B. americanus, P. cinereus, R. sylvatica, S. minor, S. varia*). Patch area models were expected to best fit species with large minimum patch size requirements (*S. aurocapilla, S. canadensis*) and patch isolation models were expected to best fit species with intermediate dispersal abilities (*D. pileatus*). The models selected by these simple trait-based rules matched the model that was best supported by the data for 4 of the 8 focal species (*B. americanus, D. pileatus, S. minor, S. aurocapilla*; Table 3).

Model parameterization

Following the statistical framework, we fit a patch area model (SAR), a patch isolation model (MEP) and an environmental condition model (SDM) with a binomial error structure and logit link for each focal species. The response for each model was the presence/pseudo-absence of the focal species in a patch. We used a 1:1 presence:pseudo-absence sampling scheme with 100 different pseudo-absence data sets for each species. Sampling effort was not spatially homogeneous and varied for each species (Fig. A1). We accounted for this by biasing our pseudo-absence selection to patches in which the density of observations was higher (for a given guild: amphibians and birds separately). For a given species, pseudo-absences were thus drawn more frequently in those patches that had a high density of observations of other species but in which the focal species did not occur (see Fig. A1). Note that for birds, only the five selected species were considered in the sampling effort while for amphibians we considered all the amphibian species occurring in the database (N = 20).

We used stepAIC to determine the most parsimonious set of covariates for each model class per set of pseudo-absences (n = 100) per species (n = 8). The patch area model (SAR) included $\log_{10}$(patch area) as a covariate and the patch isolation model (MEP) included $\log_{10}$(species-weighted sum of distances to neighboring patches) as a covariate. We identified neighboring nodes using a minimum planar graph (MPG; Fall et al. 2007). This approach approximates the shortest straight-line distance between neighboring patches but links in the MPG may not exactly correspond to the minimum inter-patch distance due to the influence of surrounding habitat patches (Fall et al. 2007). While there is evidence that patch area may influence metapopulation dynamics, in order to differentiate between the SAR and MEP models, we only included isolation effects in MEP model. We included all the environmental variables (i.e. soil drainage, soil deposit, % deciduous forest, % coniferous forest and maximum forest stand age) as potential covariates in our environmental conditions model (SDM) for all species. For anuran species, the environmental condition model also included the presence of wetlands as a covariate because wetlands are essential habitat for this taxa. For all patch area, patch isolation, and environmental condition models, we tested linear and quadratic terms for each covariate but did not include covariate interaction terms.

For each pseudo-absence iteration per species, we used AIC to rank the patch area, patch isolation, and environmental condition models relative to each other. We assumed the model class with the lowest AIC was best supported by the data. Finally, we calculated the percentage of total pseudo-absence iterations (n = 100) for which the patch area, patch isolation, and environmental condition model was ranked as the best model for each species. To further assess patch area, patch isolation, and environmental condition model predictive accuracy, we measured the mean True Skill Statistic (TSS, Allouche et al. 2006) and the Area Under the receiver operating Curve (AUC) for each model class and species across the 100 pseudo-absence iterations.

Spatial predictions of species occurrences under current and future land-use scenarios

We describe our approach to compare spatial predictions of species occurrences under current and future landscape scenarios in the main text. To define our future landscape, we applied a "Business As Usual" (BAU) landscape change scenario where current trends of land-use development in our study region are maintained to 2050. Specifically, most agricultural land is protected from urbanization due to agricultural zoning (Jobin et al. 2010) but only current protected natural areas are protected from further developments (1.2% of the St Lawrence terrestrial lowlands). In the simulation, we consider no specific policy regulation on deforestation and we do not model changes in forest attributes (i.e. forest age does not change). Overall, 10% of the initial lowland forested habitat is lost and the new habitat network in the lowlands is composed of 9,585 (+32 %) patches with a median patch area of 18,900 m^2 (-55 %).

References

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Appendix 2 – Model predictive accuracy statistics for patch area, patch isolation, and environmental condition models for each focal species.

Table A1. Model predictive accuracy statistics for patch area (SAR), patch isolation (MEP), and environmental condition (SDM) models for each focal species measured as the TSS (True Statistic Skill) and AUC (Area Under the receiver operating characteristic Curve).

species	model type	metrics	
		TSS	ROC
Bufo americanus	SAR	0.21	0.62
	MEP	0.18	0.61
	SDM	0.24	0.67
Dryocopus pileatus	SAR	0.27	0.65
	MEP	0.26	0.67
	SDM	0.25	0.67
Plethodon cinereus	SAR	0.69	0.90
	MEP	0.42	0.76
	SDM	0.64	0.85
Rana sylvatica	SAR	0.31	0.70
	MEP	0.23	0.65
	SDM	0.33	0.71
Scolopax minor	SAR	0.39	0.72
	MEP	0.28	0.66
	SDM	0.37	0.73
Seiurus aurocapilla	SAR	0.50	0.77
	MEP	0.41	0.72
	SDM	0.43	0.75
Sitta canadensis	SAR	0.37	0.73
	MEP	0.39	0.74
	SDM	0.36	0.71
Strix varia	SAR	0.39	0.71
	MEP	0.35	0.71
	SDM	0.34	0.71

Appendix 3 – Spatial patterns of change in species richness predictions for patch area, patch isolation, and environmental condition models between the current and future (2050) landscape.

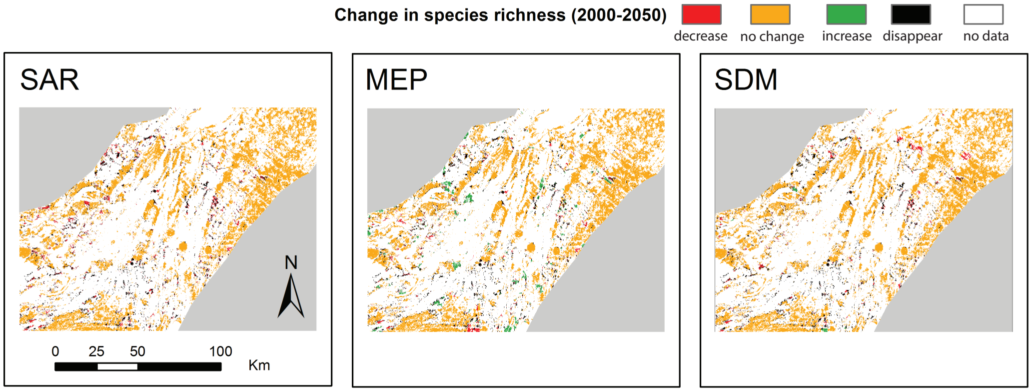

Figure A2. Spatial patterns of change in species richness (Eq. 4 multiplied by 1000) predictions for patch area (SDM), patch isolation (MEP), and environmental condition (SDM) models between the current and future (2050) landscape. The two species (*B. americanus*, *D. pileatus*) with poor model fit were excluded from the species richness calculation. Colors on the map represent non-habitat (white), forest patches lost with land-use change (black), forest patches that keep stable species richness predictions (orange; -75 to +75), forest patches with a predicted loss of species richness over time (red; -75 to -1000) and forest patches with a predicted gain of species richness over time (green; +75 to +300).